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Abstract: U-Pb data are reported for two rocks from the Scotia–Quaal metamorphic belt. A metavolcanic gneiss yields an igneous crystallization age of 370.3 ± 2.8 Ma, an age for metamorphic zircon growth of 66.4 ± 0.7 Ma, and a titanite cooling age of 62.0 ± 0.8 Ma. A detrital zircon grain from a quartzite yields an interpreted crystallization age of 386 +67/-70 Ma, giving a maximum age for deposition of the quartzite protolith that is synchronous with arc igneous activity in the area. Another detrital zircon from the same sample is Late Archean to Early Paleoproterozoic; indicating a cratonal source for the quartzite protolith. These ages and mildly evolved Nd-Sr isotopic data suggest a mixed active arc-cratonal provenance for the quartzite. Latest Cretaceous metamorphic zircon growth and Paleocene titanite cooling ages recorded across much of the northern Scotia–Quaal belt reflect the intrusion of the composite Quottoon pluton.

Résumé : Des données U-Pb sont présentées pour deux roches de la ceinture métamorphique de Scotia-Quaal. La datation d'un gneiss d'origine volcanique a révélé un âge de cristallisation magmatique de 370,3 ± 2,8 Ma, un âge de croissance métamorphique des cristaux de zircon de 66,4 ± 0,7 Ma, ainsi qu'un âge de refroidissement de la titanite de 62,0 ± 0,8 Ma. Un grain de zircon détritique contenu dans un quartzite a révélé un âge de cristallisation que l'on situe à 386 +67/-70 Ma. Ainsi, selon cette valeur qui définit l'âge maximal du dépôt du protolite quartzitique, la sédimentation serait contemporaine de l'activité magmatique d'arc dans la région. Un autre zircon détritique présent dans le même échantillon remonte à l'Archéen tardif ou au Paléoprotérozoïque précoce, ce qui indique que la source du protolite quartzitique est cratonique. Ces âges, ainsi que les données isotopiques du couple Nd-Sr qui témoignent d'une légère évolution laissent supposer que la source du quartzite correspond à un milieu mixte, combinant le craton et un arc actif. Un peu partout dans la partie nord de la ceinture de Scotia-Quaal, les âges de croissance métamorphique du zircon du Crétacé terminal et les âges de refroidissement de la titanite du Paléocène qui sont mesurés témoignent de l'intrusion du pluton composite de Quottoon.

INTRODUCTION

The Jurassic to Eocene Coast Plutonic Complex is an approximately 1800 km long batholithic complex that underlies most of the Coast Belt of British Columbia and adjacent areas of southeastern Alaska and southwestern Yukon. This belt of granitoid rocks obscures the boundary between the Insular and Intermontane superterranes (Monger et al., 1982; Fig. 1). Polydeformed and metamorphosed supracrustal rocks exposed in pendants and septa within the Coast Plutonic Complex provide a partial record of the prebatholithic history and later metamorphism and deformation (e.g. Gareau, 1991a; Gareau and Woodsworth, 2000; Gehrels et al., 1992; Gehrels and Boghossian, 2000). Part of this record is preserved in the Scotia–Quaal metamorphic belt (also referred to as the Ecstall pendant), a nearly 80 km long and 10 to 15 km wide belt of amphibolite-grade metamorphic rocks located southeast of Prince Rupert, British Columbia. (Fig. 1b).

In this study we report U-Pb dates for two rocks, a metavolcanic gneiss and a quartzite from the Scotia–Quaal belt that supplement previous dating by Gareau (1991a, b, 1991c). These dates provide constraints on depositional age, provenance, and age of metamorphism of the strata in the Scotia–Quaal belt. We discuss these dates in the context of questions regarding the regional correlation of the Scotia–Quaal belt, and the effects on Scotia–Quaal belt rocks of latest Cretaceous and Paleocene magmatism and metamorphism in the Central Gneiss Complex to the east.

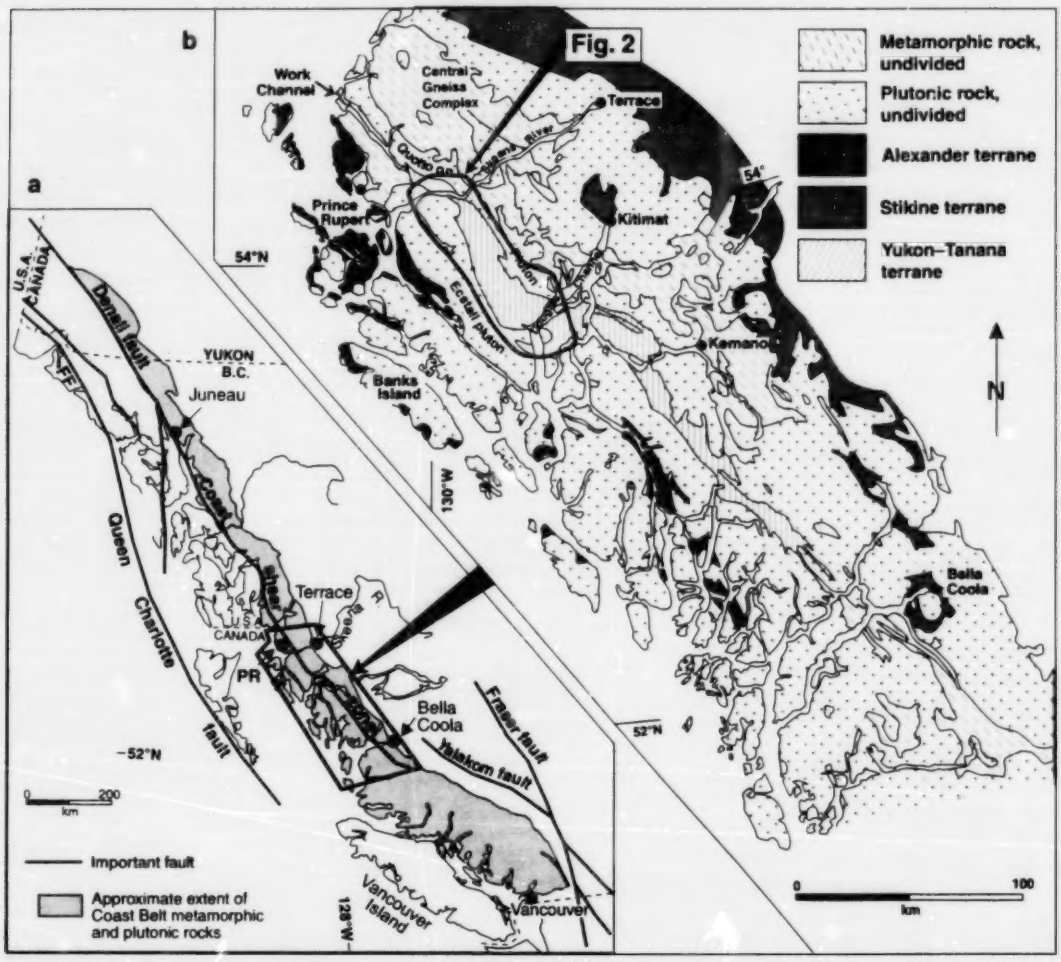

Figure 1. a) *Outline map of the western Canadian Cordillera showing extent of Coast Belt metamorphic and plutonic rocks and location of Coast shear zone.* ***b)*** *Generalized geology of the Coast Belt between Prince Rupert and Bella Coola* (after *Gareau and Woodsworth, 2000*).

GEOLOGY OF THE SCOTIA–QUAAL METAMORPHIC BELT

The Scotia–Quaal belt is bounded on the west by the early Late Cretaceous Ecstall pluton and on the east by the Paleocene Quottoon pluton (Fig. 2). It is also bounded along its eastern margin by the Coast shear zone, an approximately 1200 km long north-northwest-trending, steeply northeast-dipping zone of Paleocene, ductile, northeast-side-up, reverse displacement that, at this latitude, mainly involves rocks of the Quottoon pluton (Fig. 1a; Rusmore et al., in press).

The geology of the Scotia–Quaal belt has been described by Gareau (1991a, b) and Gareau and Woodsworth (2000), and references therein, and the following summary is taken from their work. Rocks of the Scotia–Quaal belt are mainly amphibolite-grade meta-igneous and metasedimentary rocks of Paleozoic to possibly Late Proterozoic age, and Early Jurassic orthogneiss that intruded them. The Paleozoic igneous rocks have been interpreted as an arc that was built on, and intruded into, a sedimentary sequence of continental margin affinity. This composite Middle Paleozoic to possibly Late Proterozoic sequence has been correlated with the Yukon–Tanana terrane, which, in the Coast Belt, occurs along strike to the north and south (Gehrels et al., 1992; Gehrels and Boghossian, 2000; Gareau and Woodsworth, 2000).

Scotia–Quaal belt metasedimentary rocks include quartzite and associated minor metapelitc schist, and biotite-hornblende-epidote±garnet gneiss that Gareau (1991a) referred to as the metaclastic unit. Detrital zircon data presented below provide a maximum depositional age for the sedimentary protoliths of one quartzite unit.

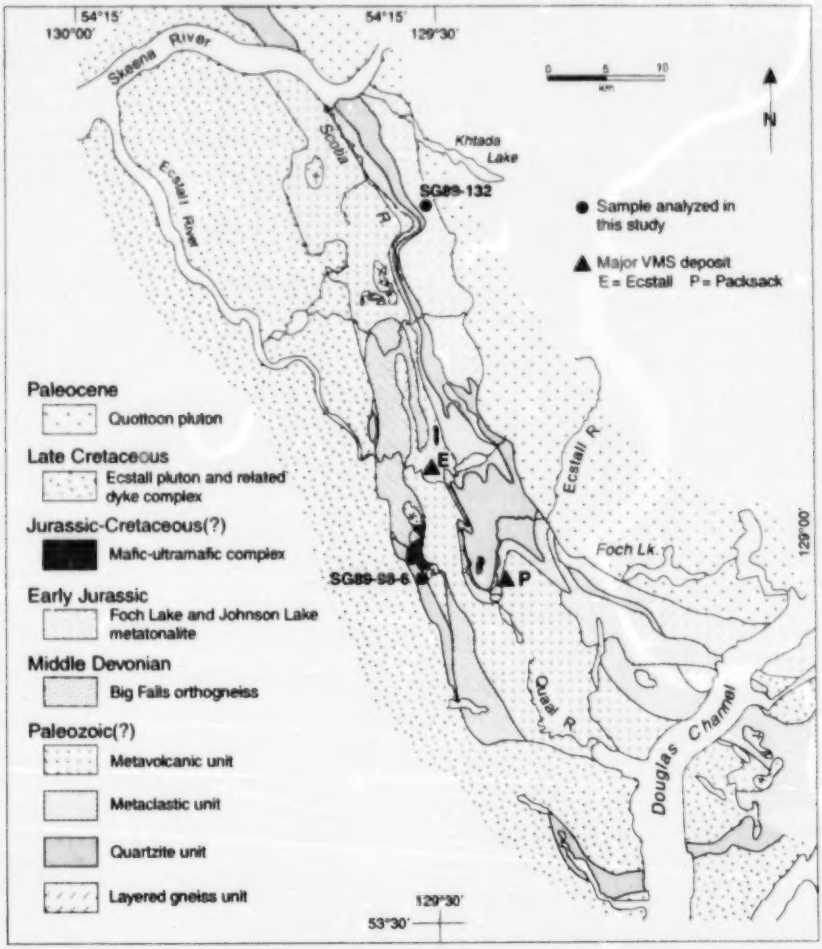

Figure 2. *Simplified geological map of the Scotia–Quaal belt* (after *Gareau and Woodsworth 2000*), *showing location of samples and the two main volcanogenic massive-sulphide (VMS) deposits in the area.*

The Big Falls tonalite orthogneiss, the largest meta-intrusive unit within the Scotia–Quaal belt, yielded a U-Pb zircon crystallization age of 385 ± 4 Ma (Gareau, 1991a). Along its eastern margin, orthogneiss grades into finer grained rocks of similar composition, interpreted as metavolcanic equivalents (Gareau and Woodsworth, 2000). In the southern part of the belt, the Ecstall and related volcanogenic massive-sulphide deposits are hosted in rocks of the metavolcanic unit (Fig. 2; Alldrick, 2001; Alldrick et al., 2001).

Younger magmatic suites that intruded Paleozoic rocks of the Scotia–Quaal belt include Early Jurassic orthogneiss (Foch Lake and Johnson Lake bodies of Gareau, 1991a) with interpreted U-Pb zircon crystallization ages of ca. 190 Ma, and Early Cretaceous (ca. 115 Ma) mafic-ultramafic bodies (Gareau, 1991a). The Early Jurassic suite predates most Coast Plutonic Complex magmatism, overlaps in age with igneous rocks of the Hazelton arc, and may provide local evidence for Early Jurassic proximity of the Yukon–Tanana and Stikine terranes. The Early Cretaceous suite is similar in age to Alaskan-type ultramafic rocks exposed to the west in southeastern Alaska (Woodsworth et al., 1991; Saleeby, 1992).

At least two phases of regional metamorphism and deformation have been recognized in the Scotia–Quaal belt: an early phase that postdated deposition of Middle Paleozoic and older sedimentary and volcanic rocks and predated intrusion of Early Jurassic orthogneiss protoliths; and a later, main phase, that took place after intrusion of Early Jurassic orthogneiss protoliths, but before intrusion of the Early Cretaceous mafic-ultramafic suite (Gareau and Woodsworth, 2000). Paleocene contact metamorphism has been documented along the eastern contact with the Quottoon pluton (Gareau and Woodsworth, 2000).

U-Pb GEOCHRONOLOGY

We report new U-Pb data for two rocks from the Scotia–Quaal belt. One is a layered gneiss from the east side of the Scotia–Quaal belt that yielded both zircon and titanite; the other is a quartzite from which detrital zircon grains were recovered. Sample locations are shown on Figure 2. Locations and U-Pb data are listed in Table 1 and results are plotted on standard concordia diagrams in Figure 3. Interpreted ages and their local and regional significance are discussed below. Geochronological analysis was undertaken at the geochronology laboratory at the

Table 1. U-Pb analytical data for rocks from the Scotia–Quaal belt.

Fraction[1]	Wt	U[2]	Pb*[3]	$^{206}Pb/^{204}Pb$[4]	Pb[5]	^{208}Pb[6]	Isotopic ratios (1σ,%)[7]						Apparent ages (2σ,Ma)[7]					
	mg	ppm	ppm		pg	%	$^{206}Pb/^{238}U$		$^{207}Pb/^{235}U$		$^{207}Pb/^{206}Pb$		$^{206}Pb/^{238}U$		$^{207}Pb/^{235}U$		$^{207}Pb/^{206}Pb$	
SG89-132: Layered gneiss; 54°5.22'N 129°30.04'W																		
A c,cl,co,eq,r	0.173	1402	18	20181	10	4.4	0.01332	(0.11)	0.0903	(0.19)	0.0492	(0.09)	85.3	(0.2)	87.8	(0.3)	155.7	(4.3)
B c,cl,co,eq,r	0.140	896	12	15880	7.0	5.7	0.01428	(0.13)	0.0978	(0.20)	0.0497	(0.10)	91.4	(0.2)	94.8	(0.4)	179.9	(4.8)
C c,cl,co,eq,r	0.134	1818	25	22524	9.0	9.2	0.01377	(0.11)	0.0936	(0.11)	0.0493	(0.02)	88.2	(0.2)	90.9	(0.2)	162.8	(0.9)
D c,cl,pi,s,p	0.083	373	20	8803	11	17	0.04913	(0.11)	0.3629	(0.19)	0.0536	(0.10)	309.2	(1.0)	314.4	(1.0)	353.2	(4.5)
E c,cl,pi,p,e	0.152	451	22	19765	9.8	17	0.04522	(0.09)	0.3338	(0.09)	0.0535	(0.02)	285.1	(0.5)	292.5	(0.5)	352.0	(1.1)
G c,cl,pi,p,s	0.090	718	29	5473	28	13	0.03831	(0.09)	0.2811	(0.17)	0.0532	(0.09)	242.3	(0.5)	251.6	(0.8)	338.3	(4.1)
H c,cl,pi,p,s	0.123	402	21	17060	8.6	16	0.04737	(0.08)	0.3507	(0.15)	0.0537	(0.08)	298.4	(0.5)	305.3	(0.8)	358.4	(3.4)
I c,cl,co,eq,r	0.065	1160	16	8921	7.7	5.2	0.01464	(0.08)	0.1007	(0.16)	0.0499	(0.09)	93.7	(0.2)	97.4	(0.3)	188.7	(4.0)
J m,cl,co,p,s	0.024	305	13	1912	10	11	0.04196	(0.11)	0.3083	(0.26)	0.0533	(0.21)	265.0	(0.5)	272.8	(1.2)	340.9	(9.4)
K f,cl,co,p,s	0.059	474	15	8563	6.1	12	0.03006	(0.09)	0.2183	(0.16)	0.0527	(0.09)	190.9	(0.4)	200.5	(0.6)	314.8	(3.9)
T1 cc,cl,y,b	0.825	247	3.1	145	963	30	0.00961	(0.27)	0.0626	(1.3)	0.0473	(1.1)	61.6	(0.3)	61.7	(1.5)	64	(52/54)
T2 cc,cl,y,b	0.795	251	3	148	953	28	0.00971	(0.44)	0.0634	(1.6)	0.0473	(1.3)	62.3	(0.5)	62.4	(1.9)	64	(60/63)
SG89-98-6: Quartzite - detrital single grains; 53°47.28'N 129°31.71'W																		
A ff,cl,co,s,p	0.001	376	22	193	8.0	9.5	0.05958	(0.20)	0.4465	(1.6)	0.0544	(1.5)	373.1	(1.5)	375	(10)	386	(67/70)
B ff,cl,pi,eu,p	0.001	1670	29	96	25	0.8	0.01857	(0.45)	0.1902	(2.3)	0.0743	(2.1)	118.6	(1.1)	176.8	(7.5)	1050	(82/86)
C ff,cl,pi,s,p,r	0.001	161	86	856	5.6	11	0.46876	(0.15)	11.385	(0.24)	0.1762	(0.16)	2478.1	(6.2)	2555.3	(4.4)	2617.1	(5.2)

1 Upper case letter = zircon fraction identifier; T1, T2, etc. for titanites. All zircons except detrital grains air abraded. Grain size, intermediate dimension: cc=>250 μm, c=<250 μm and >134 μm, m=<134 μm and >104 μm, f=<104 μm and >74 μm, ff <74 μm; Grain character codes: b= broken; cl=clear; co=colourless; e=elongate, eq=equant; eu=euhedral, p=prismatic, pi=pale pink; r=rounded; s=stubby; y=yellow. Zircons nonmagnetic on Franz magnetic separator at field strength of 1.8A and sideslopes of 1°–5°. Titanites nonmagnetic at 0.6A and 20° sideslope, and magnetic at 1.8A and 5° sideslope. Front slope of 20°fc. all.

2 U blank correction of 1pg ±20%; U fractionation corrections were measured for each run with a double ^{233}U-^{235}U spike (about 0.004/amu).

3 Radiogenic Pb

4 Measured ratio corrected for spike and Pb fractionation of 0.0043-0.0035/amu ± 20% (Daly collector), which was determined by repeated analysis of NBS Pb 981 standard throughout the course of this study.

5 Total common Pb in analysis based on blank isotopic composition.

6 Radiogenic Pb

7 Corrected for blank Pb (1-10pg), U (1pg) and common Pb isotopic compositions based on Stacey-Kramers model Pb at the age or the $^{207}Pb/^{206}Pb$ age of the rock.

Department of Earth and Ocean Sciences, University of British Columbia, following the analytical techniques given in Friedman et al. (2001).

Layered gneiss (sample SG89-132)

Sample SG89-132 was collected in the northeastern part of the Scotia–Quaal belt, about 1 km from the intrusive contact with the Paleocene Quottoon pluton (Fig. 1b). The sample is from the layered gneiss unit of Gareau (1991a), which she interpreted as metavolcanic in origin. Ubiquitous decimetre-scale layering in this unit is defined by the relative abundances of mafic minerals. Felsic layers are fine to medium grained, dioritic to granodioritic in composition (locally migmatitic) and are composed predominantly of quartz, oligoclase to andesine, hornblende, and biotite in various proportions. Zoisite, garnet, and retrograde chlorite and sericite occur locally. Accessory minerals include titanite, zircon, opaque minerals, and locally, rutile. Mafic layers most commonly consist of medium-grained amphibolite with more than 55% mafic minerals (hornblende, biotite, and chlorite) and lesser amounts of garnet, quartz, and oligoclase to andesine (Gareau, 1991a).

About 20 kg of gneissic rock from relatively felsic, but nonmigmatitic layers in this unit were processed employing standard crushing, Wilfley table, and heavy liquid techniques outlined in Friedman et al. (2001). Both zircon and titanite were recovered. Zircon comprises two distinct populations: pink stubby to elongate prismatic grains with abundant opaque micro-inclusions, and clear, colourless, gem-quality, subequant, subrounded to stubby, prismatic grains. Ten strongly abraded multigrain zircon fractions were analyzed. On a concordia diagram (Fig. 3A) the results define a linear array through which a regression line was fitted. U-Pb results for six fractions of pink grains are widely dispersed along the upper two-thirds of the regression line (fractions D, E, G, H, J, and K). Four fractions of clear grains (fractions A, B, C and I) yielded much younger Pb/U and $^{207}Pb/^{206}Pb$ apparent ages that are less dispersed and plot near the lower intercept of the regression line. The two populations also exhibit systematic variations in U concentrations and model Th/U values (Table 1; the latter values expressed as % ^{208}Pb). Pink grains are interpreted as magmatic in origin, and the upper intercept of 370.3 ± 2.8 Ma is taken as an estimate of the crystallization age of the volcanic protolith. We interpret the clear grains to be metamorphic in origin, based mainly on their characteristic subround morphology and younger apparent ages. Migmatitic rock was not observed in the sampled material, and we consider it unlikely

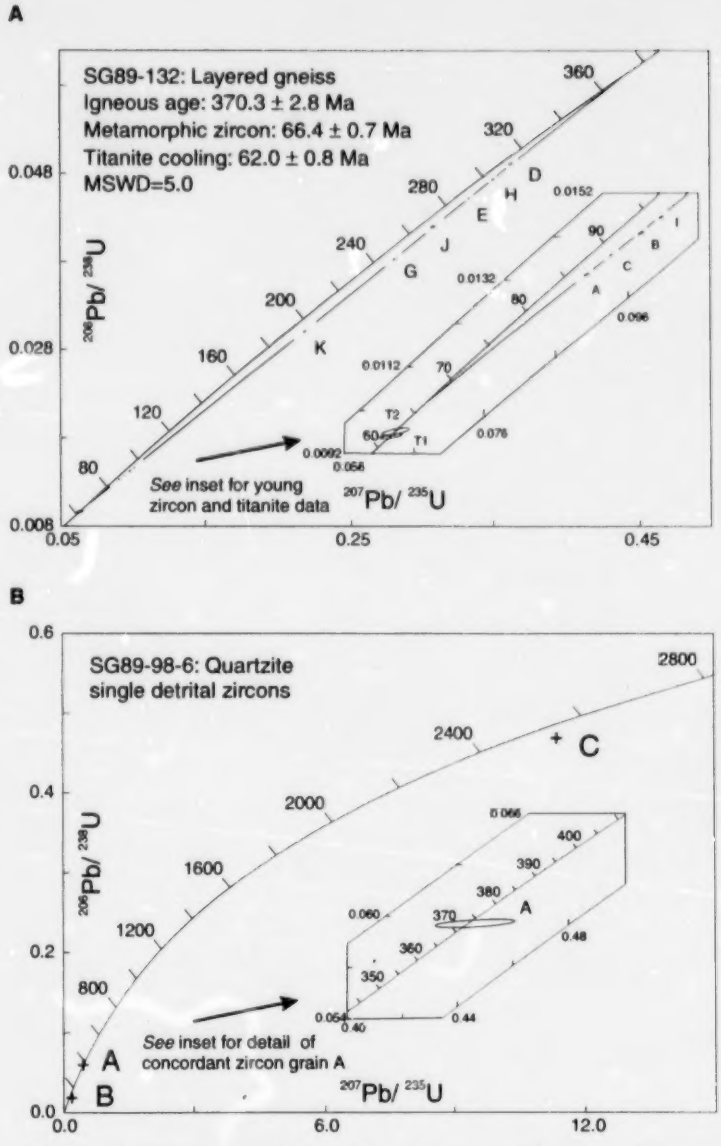

Figure 3. *Uranium-lead concordia diagrams with error ellipses plotted at the 2σ level of uncertainty. A) Layered gneiss sample SG89-132. B) Quartzite sample SG89-98-6. Fractions A, B and C on the main diagram are plotted as crosses that do not reflect analytical uncertainty. See Table 1 for precisions and inset with ellipse for fraction A plotted at the 2σ level of uncertainty.*

that clear grains are of young magmatic origin. The lower intercept age of 66.4 ± 0.7 Ma is interpreted to record when these grains crystallized. The minor dispersion of results for clear grains may reflect the presence of minor amounts of inherited magmatic zircon. The much greater dispersion of results for pink grains is probably due to the presence of high-U metamorphic overgrowths and/or Pb-loss.

Titanite from sample SG89-132 is clear, pale yellow, and occurs as subhedral disc-shaped grains, and, more commonly, as blocky broken fragments. Two unabraded fractions yielded concordant and overlapping $^{206}Pb/^{238}U$ results of 62.0 ± 0.8 Ma (Fig 3A, T1, T2), which we take as the time at which these grains cooled below the titanite closure temperature. Estimates of the closure temperature of titanite vary from ~500°C (Mattinson, 1982) to ~700°C (Frost et al., 2000), depending on grain size, cooling and strain rates, and composition.

Quartzite (sample SG89-98-6)

Our sample of white quartzite is from the central-western part of the Scotia–Quaal metamorphic belt, about 1 km east of the Ecstall pluton (Fig. 2). The sample is composed dominantly of fine-grained (< 1 mm across) granoblastic quartz, with minor zoisite (~5%), cummingtonite (2% or less), muscovite (1% or less), and carbonate (1% or less).

Some 3 kg of quartzite yielded only a small quantity of zircon, and only three grains were large enough to date as single crystals. Due to their small size, the three analyzed grains were not air-abraded. Grain A was a clear, colourless, euhedral prismatic grain about 100 µm long with width and breadth of about 40 µm. The results intersect concordia within error and are 3% discordant, with a $^{207}Pb/^{206}Pb$ date of 386 +67/-70 Ma, interpreted as the crystallization age for this detrital grain (Fig. 3B, Table 1). Grain B was a clear, pale pink zircon about 110 µm by 30 µm by 30 µm. It gave strongly discordant results, with Mesozoic Pb/U apparent ages and a ca. 1 Ga $^{207}Pb/^{206}Pb$ date (Table 1). Such discordance is attributed to Pb-loss and/or the presence of a significant metamorphic rim. Grain C was a pale pink, very clear, cylindrical grain with a length of ~80 µm and a diameter of ~25 µm. It yielded discordant results (~6%) with a $^{207}Pb/^{206}Pb$ date of 2617.1 ± 5.2 Ma, and is conservatively interpreted to have crystallized during the Late Archean or Early Paleoproterozoic.

DISCUSSION AND CONCLUSIONS

We take the interpreted igneous crystallization age of 370.3 ± 2.8 Ma for the layered gneiss sample (SG89-132) as evidence of Late Devonian arc volcanism. This age is slightly younger than, or overlaps, the age of igneous activity inferred from other dated rocks in the belt (Big Falls orthogneiss, 385 ± 4 Ma; Gareau, 1991; quartz diorite sill at the Ecstall VMS deposit, 377 +9/-4 Ma, Alldrick et al., 2001; and a felsic metavolcanic rock, 393 ± 12 Ma, Alldrick et al., 2001). Such dates are characteristic of the age of arc activity along much of the Coast Belt portion of the Yukon–Tanana terrane (Gehrels, in press; Gehrels et al., 1992; Gareau and Woodsworth, 2000). The dates are also similar to those from the igneous rocks of the Devonian part of the Stikine assemblage (Gunning, 1996) in the Stikine terrane east of the Coast Belt.

The interpreted crystallization age of 386 +67/-70 Ma for a detrital zircon grain from the quartzite sample (SG89-98-6) gives a maximum depositional age for its sedimentary protolith, indicating that arc activity and basin formation were possibly in part synchronous. A detrital zircon grain from the same sample with an interpreted Precambrian crystallization age is consistent with a cratonic source. A mixed arc-craton source for Scotia–Quaal belt quartzite is consistent with the mildly evolved initial Nd-Sr values from this unit (εNd_t and Sr_i values of about -2 and >0.705, respectively, reported by Gareau and Woodsworth, 2000).

Meta-igneous and metasedimentary rocks of the Scotia–Quaal belt were correlated by Gareau and Woodsworth (2000) with the Coast Belt segment of the Yukon–Tanana terrane, based on their along-strike location, lithological character, timing of igneous activity, and Nd-Sr isotopic signature. Our data support this correlation. A Lower Paleozoic and possibly older supracrustal assemblage found within northern Coast Belt segment of the Yukon–Tanana terrane (the Tracey Arm Assemblage of Gehrels et al., 1992) has not yet been directly dated in the Scotia–Quaal belt, but possibly comprises part of the succession into which Middle Paleozoic intrusions such as the Big Falls orthogneiss were emplaced.

An age near the Cretaceous-Tertiary boundary (66.4 ± 0.7 Ma) for metamorphic zircon and a Paleocene titanite cooling age (62.0 ± 0.8 Ma) from layered gneiss sample SG-89-132, may broadly coincide with intrusion of the composite Quottoon pluton; the western contact of the pluton is about 1 km from the sampled gneiss. Two U-Pb dated samples from the Quottoon pluton east of the Scotia–Quaal belt give significantly younger interpreted crystallization ages of ca. 56–59 Ma. (Gareau, 1991a; Rusmore et al., in press), but a nearby mylonitic tonalite gave a U-Pb crystallization age of 67 ± 1 Ma (Rusmore et al., in press). About 100 km north-northwest of the Scotia–Quaal belt, Gehrels (in press) obtained a U-Pb age of 72.3 ± 2.0 Ma from the western part of the Quottoon pluton. U-Pb data from this study and Alldrick et al. (2001) suggest that Pb-loss in zircon and/or metamorphic zircon growth in Paleozoic arc magmatic rocks are not restricted to the vicinity of the eastern margin with the Quottoon pluton, but span nearly the entire width of the northern half of the Scotia–Quaal belt.

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